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Performance Ranking of Arterial Corridors Using Travel Time and Travel Time Reliability Metrics

Christopher M. Day
Purdue University, cmday@purdue.edu

Stephen Remias
Purdue University, sremias@wayne.edu

Howell Li
Purdue University, howell-li@purdue.edu

Michelle M. Mekker
Purdue University

Margaret L. McNamara
Purdue University, mcnamar0@purdue.edu

See next page for additional authors

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Authors
Christopher M. Day, Stephen Remias, Howell Li, Michelle M. Mekker, Margaret L. McNamara, Ed Cox, and Darcy M. Bullock

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Christopher M. Day
Purdue University

Stephen M. Remias
Purdue University

Howell Li
Purdue University

Michelle M. Mekker
Purdue University

Margaret L. McNamara
Purdue University

Edward D. Cox
Indiana Department of Transportation

Darcy M. Bullock*
Purdue University
550 Stadium Mall Drive
West Lafayette, IN 47901
(765) 494-2226
darcy@purdue.edu

*Corresponding author.

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ABSTRACT

Performance measures are important for managing transportation systems and demonstrating accountability. Probe vehicle data has emerged as a means of gathering vast amounts of information about highway networks. This paper presents a scalable methodology for analyzing arterial travel times, taking into account both the central tendency of the travel time and its reliability. A pilot analysis is carried out for 28 arterials with a total of 341 signalized intersections across the state of Indiana. Starting from individual minute-by-minute speed records, the data are converted into travel times and aggregated into time series cohorts that correspond to typical traffic signal time-of-day periods, reflecting different time-of-day behavior characteristics of traffic control in arterials. The data is normalized with respect to the ideal travel time (based on the speed limits on each route) to account for individual route lengths and speeds. Data is compiled for all Wednesdays from January through July 2014 to investigate arterial characteristics. The data shows that a greater density of traffic signals on a route loosely corresponds to higher average travel times and less reliability. A composite index incorporating both the average values and reliability characteristics of travel time is developed, and used to rank the arterials according to their performance.

INTRODUCTION

Recently, there has been an increased emphasis in developing performance measures for transportation systems, especially since the passage of the MAP-21 highway funding bill that emphasizes performance measurement. Also, the scarcity of engineering resources demands that investments be made more intelligently. In the past decade, mobile electronic devices such as smart phones have proliferated. Since these are capable of reporting their position over time, each vehicle transporting such a device has the potential to become a probe vehicle. Several commercial data providers have brought traffic data to market based on the analysis of mobile device position data.

Probe vehicle data has enabled the analysis of mobility at various levels. The *Urban Mobility Report* (*1*), for example, uses probe vehicle speeds to rank US cities by the relative amount of highway congestion experienced by the average motorist in each city. Some state agencies have invested in probe data to facilitate highway performance reporting. For example, the *Indiana Mobility Report* series (*2*) has focused on the performance of Interstate highway routes maintained by the Indiana Department of Transportation (INDOT). A variety of performance measures and visualization tools were developed (*3*) to identify the location and duration of congestion. Several other agencies have used probe data in similar analyses (*4,5,6,7*).

Arterials differ from freeways because of the influence of traffic control, particularly traffic signals. This has made their analysis more challenging. Numerous previous studies have focused on the measurement and estimation of arterial travel times (*8,9,10,11,12,13,14,15,16*), filtering and correction of arterial travel time data sets (*17,18,19,20*), analysis of arterial travel time reliability characteristics (*21,22,23*), and use of the data to generate origin-destination information and route characteristics (*24,25*). These studies have improved the understanding of arterial travel times, yet have tended to focus on a single arterial route, or a group of surface streets in the same region. There has not yet been a study focusing on the comparison and ranking by performance of many arterials distributed over a large geographic area.

This paper presents a scalable methodology for analyzing and ranking the mobility performance of arterial routes, incorporating measures of both the central tendency (average) as well as the reliability (amount of variation) of arterial travel times. Starting from individual minute-by-minute segment speed records, arterial travel times are calculated and aggregated into time series cohorts that correspond to typical traffic signal time-of-day schedules. These are combined into a composite index for use in ranking arterials for prioritization of engineering resources.

ROUTE AND DATA SELECTION

A large inventory of state-owned arterial routes exists within the state of Indiana. To begin the process of evaluating the mobility performance of these routes, it was decided to pilot the analysis methodology on a subset of the state highway network. A list of the highest priority routes was obtained from INDOT engineers for this purpose. Figure 1 shows a map of the state highway network in Indiana. The interstate routes are shown as thick blue lines, while non-interstate routes are thin black lines. The red highlighted routes represent the arterials included in the pilot study.

To accomplish the task of evaluating and comparing this set of arterials distributed throughout Indiana, this study made use of archived crowd-sourced probe data that INDOT had previously procured from a private company, which consists of minute-by-minute segment speeds. The advantage of this data set is that the roadways do not have to be instrumented to obtain the data. Instead, the data is obtained by monitoring of mobile devices in the vehicle fleet.

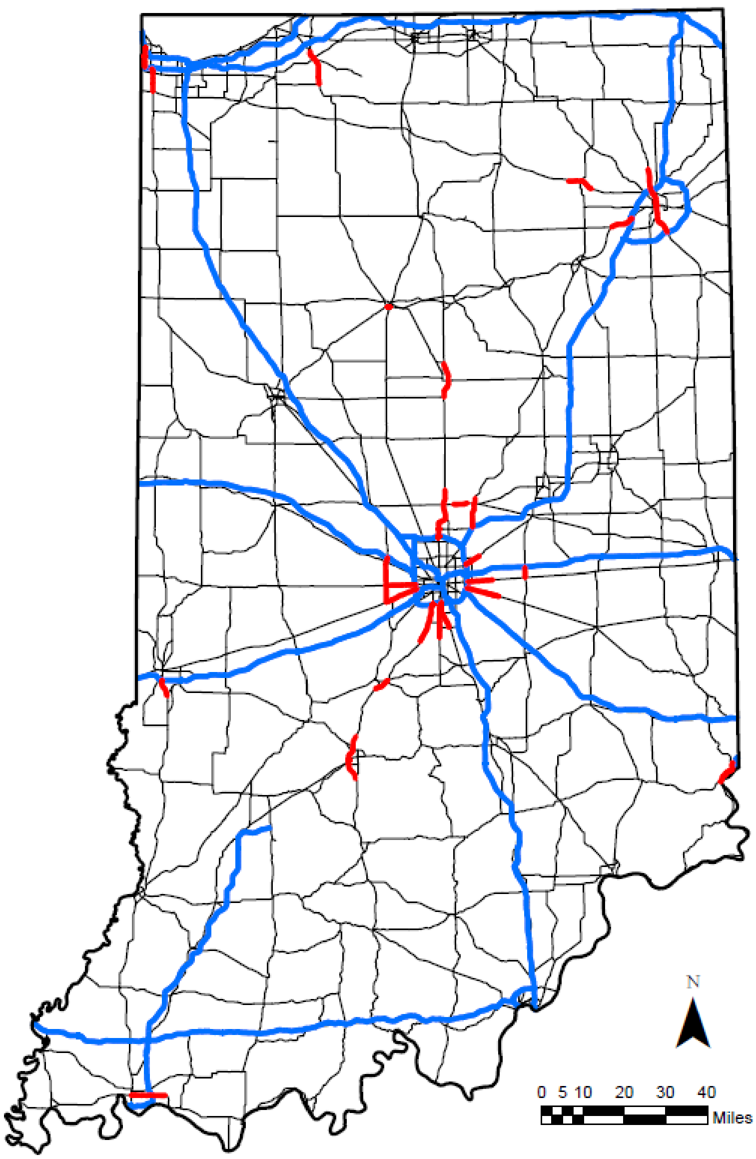


Figure 1. Locations of arterials in Indiana prioritized for mobility analysis.

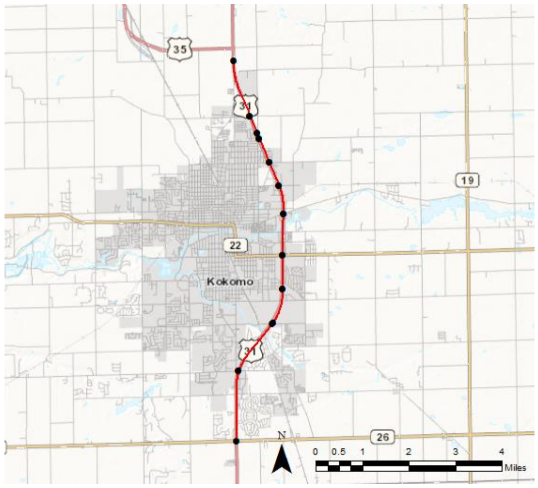
While this data has been used extensively for freeway analyses (*1*,*2*,*3*,*4*,*5*,*6*,*7*), there have been fewer attempts to use it for arterials. Researchers in the I-95 Consortium have done so with some success, and they made the following recommendations (*26*):

- The arterials should have relatively high volume (above 20,000 vehicles per day);
- The density of traffic signals should be “sparse”;
- Midblock friction should be low to moderate; and
- The through movements should dominate.

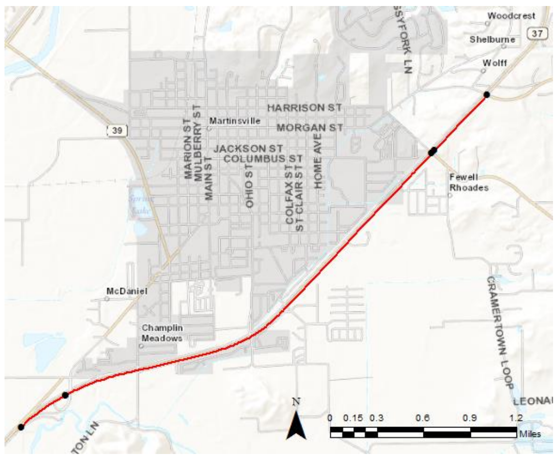
The arterials under consideration in the present paper generally match these characteristics. In another recent study (*27*), the crowd-sourced probe vehicle travel times were found to have considerably more error than vehicle re-identification based travel times. The analysis in this paper makes the assumption that, even though travel times derived from minute-by-minute segment speeds may differ from the real-world travel times, the differences should be consistent from one system to another. Further research is needed to validate this assumption across a wider variety of locations. Additionally, the probe data continues to evolve, with shorter segments becoming available recently, so future uses of the data may provide more accurate travel time estimates.

The segments used to identify speeds in the present study used Traffic Message Channel (TMC) definitions. The segment definitions were obtained from the data provider by means of a GIS shape file. Manual checking avoided spatial overlapping of the segments. Figure 2 shows detailed examples of the segment definitions for two arterials: a longer route, SR 931 in Kokomo, IN (Figure 2a), and a shorter route, SR 37 in Martinsville, IN (Figure 2b).

The INDOT contract for the data specifies that it is to be provided *without smoothing*, meaning that any minute during which no real world speeds were measured would correspond to missing data, rather than an assumed default value. At the time of writing, the speed data for arterial routes was slightly less complete than the freeway data. Figure 3 shows a profile of the amount of samples available for two different sections for the entire year of 2013. Each graphic shows the total number of minute-by-minute speeds for each hour throughout the year, with the stacked bars partitioning the data by day of week. Figure 3a shows the completeness for a freeway section, while Figure 3b shows the completeness for a nearby arterial section. Clearly, the data is very complete in the case of the interstate segment (Figure 3a), with representative data well populated for all times of day. This is less true of the arterial data (Figure 3b). While the busiest portion of the day (6:00–22:00) has relatively comprehensive coverage (albeit less than the interstate route), the overnight periods have fewer data points. Therefore, the analysis in this study is limited to the 6:00–22:00 hours.

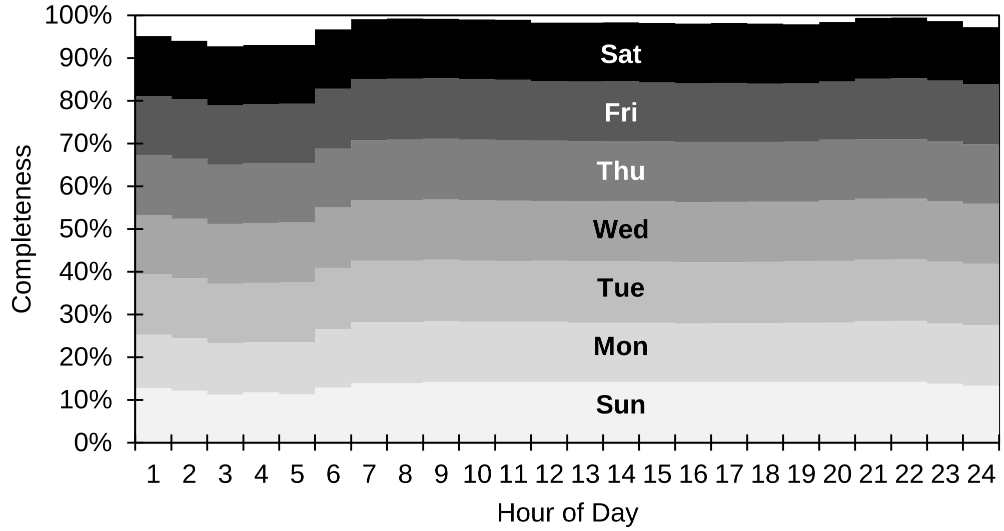


(a) SR 931 (formerly US 31), Kokomo, Indiana.

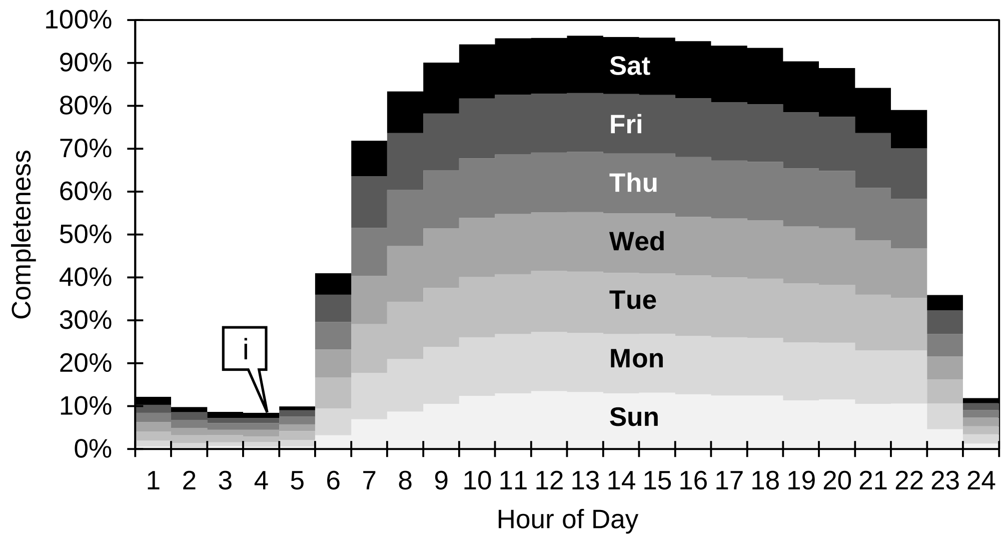


(b) SR 37, Martinsville, Indiana.

Figure 2. Map of travel time routes for example arterials.



(a) Data coverage for a typical interstate section (Westbound I-70, MM 103 to MM 95.9)



(b) Data coverage for a typical arterial section (Northbound SR 9, Greenfield, IN).

Figure 3. Comparison of interstate and arterial TMC data coverage in 2013.

ANALYSIS METHODOLOGY

Aggregation

The individual minute-by-minute speed samples are pooled into 15-minute bins to mitigate the effects of occasional missing minutes of speed data. The timeline is divided into 15-minute intervals; the average of all the minute-by-minute data points available within the 15-minute interval is taken. An example 15-minute bin is: “1/1/2014, 7:00–7:15.” Some bins have slightly fewer than 15 data points available. Any 15-minute bin without speed data is presumed to be operating at the speed limit. That mostly occurs during the low-volume overnight time period, which is excluded from the overall analysis in this study.

The average travel time for bin *j* (t_j) is calculated by

$$t_j = \sum_{i \in S} \frac{d_i}{v_i}, \qquad \text{Equation 1}$$

where *S* is the set of segments defining the corridor (with each direction considered seperately), d_i is the length of the i^{th} segment, and v_i is the average speed on the i^{th} segment during bin *j*.

The remainder of the analysis relies upon the definition of time series for dividing up the data into cohorts of similar operational conditions for analysis. The average travel time *t* during a given time series *T* is found from

$$x_T = \frac{1}{N_T} \sum_{j \in T} t_j , \qquad \text{Equation 2}$$

where x_T is the average associated with time series *T*, and N_T is the number of 15-minute bins contained within the time series. An example of a time series definition is: “All Wednesdays, from 1/1/2014 through 8/1/2014, during the PM Peak (15:00–19:00).”

Normalization

An inherent problem with comparisons of travel times is that different routes have differing lengths and ideal speed characteristics. Travel times must be normalized to account for these differences to facilitate comparison. Two possible normalization methods are:

1. Calculate the *travel rate* (*8*), or the travel time divided by the distance, which gives the amount of time needed to traverse one unit of distance.
2. Divide the measured travel time by the ideal travel time, which expresses the travel time as a percentage difference from ideal conditions.

For the first normalization method, the travel rate (r_T) is given by

$$r_T = \frac{x_T}{D}, \qquad \text{Equation 3}$$

where x_T is the average travel time for time series cohort *T* (Equation 2) and *D* is the total distance for the corridor.

The second normalization method requires an ideal travel time to be determined. The ideal travel time is achieved at the free flow speed. A practical surrogate for free flow speed is the speed limit. The speed limit travel time, t_0, is given by

$$t_0 = \sum_i \frac{d_i}{L_i}, \qquad \text{Equation 4}$$

where d_i is the length of the i^{th} segment (mi) and L_i is the speed limit on the i^{th} segment (mph) comprising the arterial. A separate speed limit travel time is calculated for each of the two pairs of directions along every arterial route. This represents the travel time that would be achieved when traveling at the maximum legal speed without stopping or slowing because of traffic control, queuing, or other impedances.

The ideal speed normalized travel time (x'_T), is given by

$$x'_T = \frac{x_T}{t_0} \qquad \text{Equation 5}$$

where t_0 is the speed limit travel time (Equation 4).

Figure 4 shows a comparison between travel rates and ideal speed normalized travel times for three corridors. Each point represents the result for a different monthly time series, such as the example pointed out for Wednesdays in February 2014 during the AM Peak. The chart shows that r_T and x'_T are proportionate to each other for each route. The selection of performance measure is therefore a matter of deciding the appropriate scale for the use case. The travel rate is well suited for comparing alternative routes between a common or similar origins and destinations. However, the use case in the present study is to determine the overall performance of many routes with different origins and destinations. A specified value of travel rate might be considered low for one corridor, yet considered high for another corridor with differing distance and speed characteristics. Therefore, the ideal speed normalized travel time is selected, because it facilitates comparison of many corridors against an ideal value of 100%.

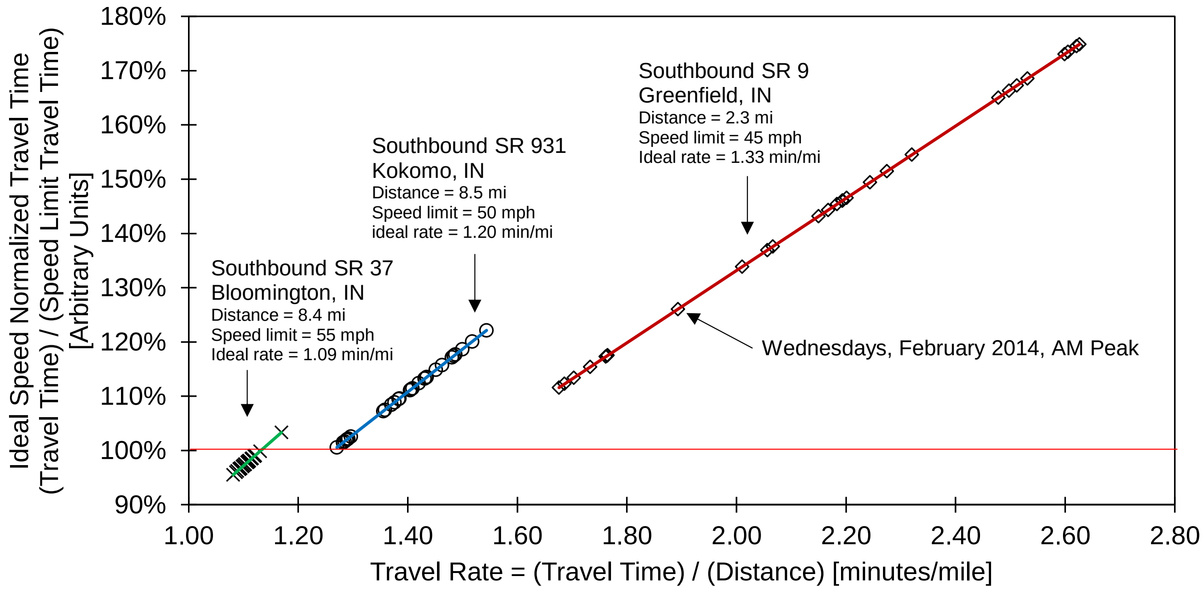
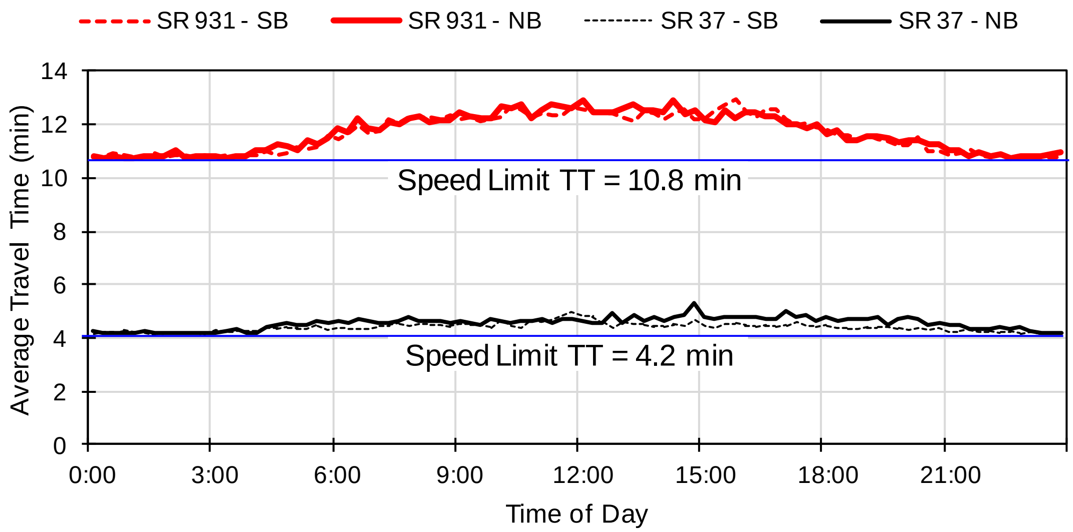


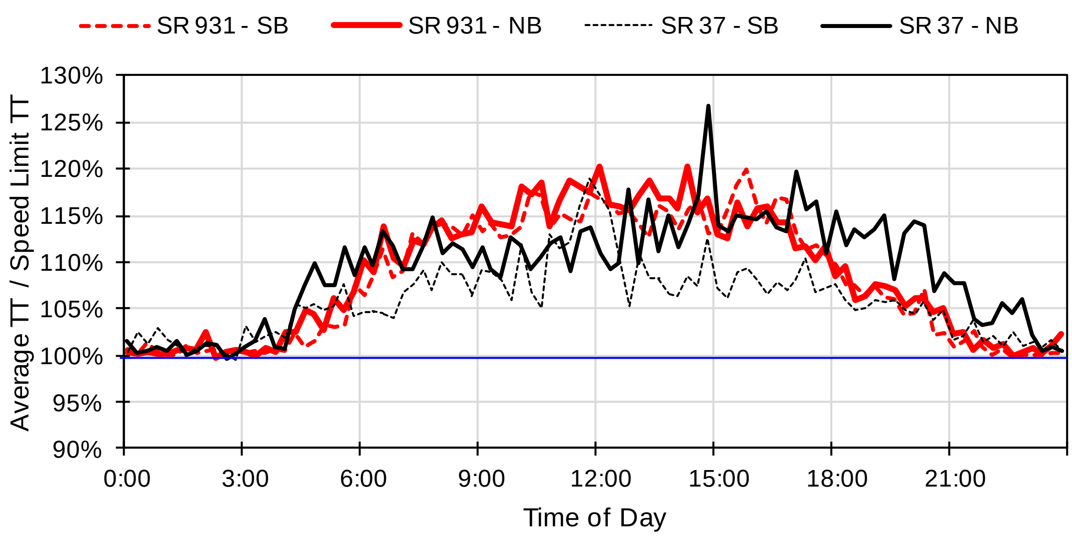
Figure 4. Comparison of travel rate (r_T) and ideal speed normalized travel time (x'_T). Speed limits shown represent the majority of segments in the corridor.

Figure 5 shows a plot of the travel times along SR 931 and SR 37 using 15-minute bins aggregated for all of the weekdays from January–July 2014. Each plot provides a 24-hour profile of the expected travel time along each route. Figure 5a shows the “raw” travel times for each route. SR 931, a longer route with a lower speed limit along some sections, has a speed limit travel time (t_0) of 10.8 minutes, while SR 37 has a speed limit travel time of 4.2 minutes. In Figure 5a, not only are the two directional curves for SR 931 in a completely different range than for SR 37, the increase in the observed travel times relative to the speed limit travel time is considerably greater for SR 931 than for SR 37.

Normalizing the observed travel times by the speed limit travel time, as shown in Figure 5b, allows the two routes to be compared. The 100% line is common to both series and corresponds to the two separate lines in Figure 5a. The normalized curves show that the time of day characteristics are somewhat different for the two arterials. Although SR 931 has a greater numerical increase in its travel times, during much of the day the percentage of increase relative to the speed limit travel time is about the same as that on SR 37. During the evening, SR 37 has a considerably greater relative increase in travel times in the northbound direction.



(a) Average of travel time, by time of day (not normalized).



(b) Normalized by speed limit travel time.

Figure 5. Normalization of central tendency of travel time.
Data is shown for Wednesdays from January–July 2014.

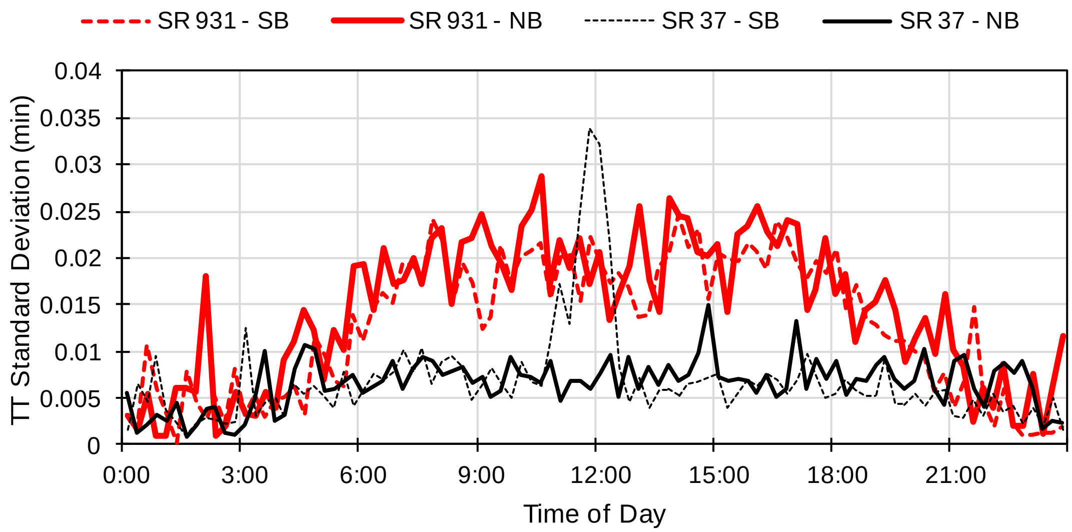
Travel Time Reliability

Beside its central tendency, the *reliability* of travel time is also a concern. A high degree of variability in travel time induces roadway users to include extra time into their trips. The standard deviation can be used to quantify the degree of variability. However, similar to the averages, the standard deviations are also dependent on the length and speed limits of the routes. These are also normalized using the speed limit travel times:

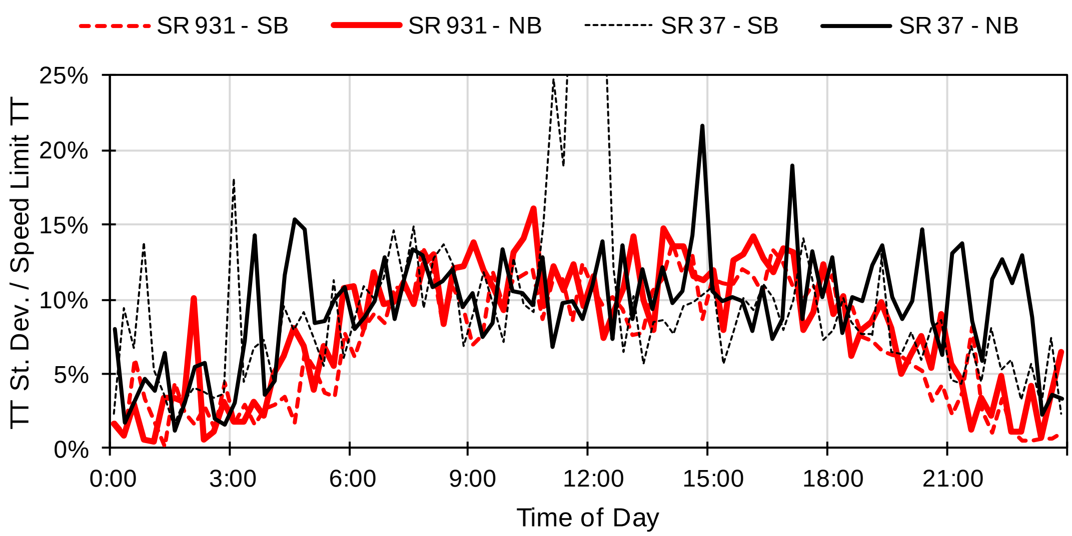
$$s'_T = \frac{s_T}{t_0} \qquad \text{Equation 6}$$

Here, s'_T is the normalized standard deviation and s_T is the observed (raw) standard deviation for time series T. The normalized values become a percentage of the speed limit travel time, which is a measure of the unreliability of a route (*i.e.*, greater variability leads to a greater value).

Figure 6 shows the standard deviations of travel time for SR 931 and SR 37 for each direction, first showing the raw values (Figure 6a) and the normalized values (Figure 6b). Similar to the average values, the unreliability of SR 37 appears to be smaller in Figure 6a during most times of day (except around noon), which is related to the route being shorter. After normalizing the data, the relative unreliability of SR 37's travel times are shown to actually be greater than SR 931 (Figure 6b) for nearly all of the day.



(a) Standard deviation of travel time, by time of day (not normalized).



(b) Normalized by speed limit travel time.

Figure 6. Normalization of variability of travel time.
Data is shown for Wednesdays from January–July 2014.

SYSTEM-WIDE ANALYSIS

Ranking by Central Tendency and Unreliability

Arterial operation is characterized by the use of traffic control devices, especially traffic signals. Most of the arterials selected in the analysis feature coordinated signal systems that change their behavior by time of day. Although the boundaries of the time-of-day (TOD) patterns are not necessarily identical for all of the arterials in the state highway network, they do tend to feature three TOD patterns that run during weekdays: an AM peak pattern, a midday pattern, and a PM peak pattern. These are established to accommodate predominant traffic flow in one direction or the other during the peaks, and more balanced flows during the midday. For this reason, three corresponding TOD time series cohorts were selected for analysis of arterial travel time characteristics:

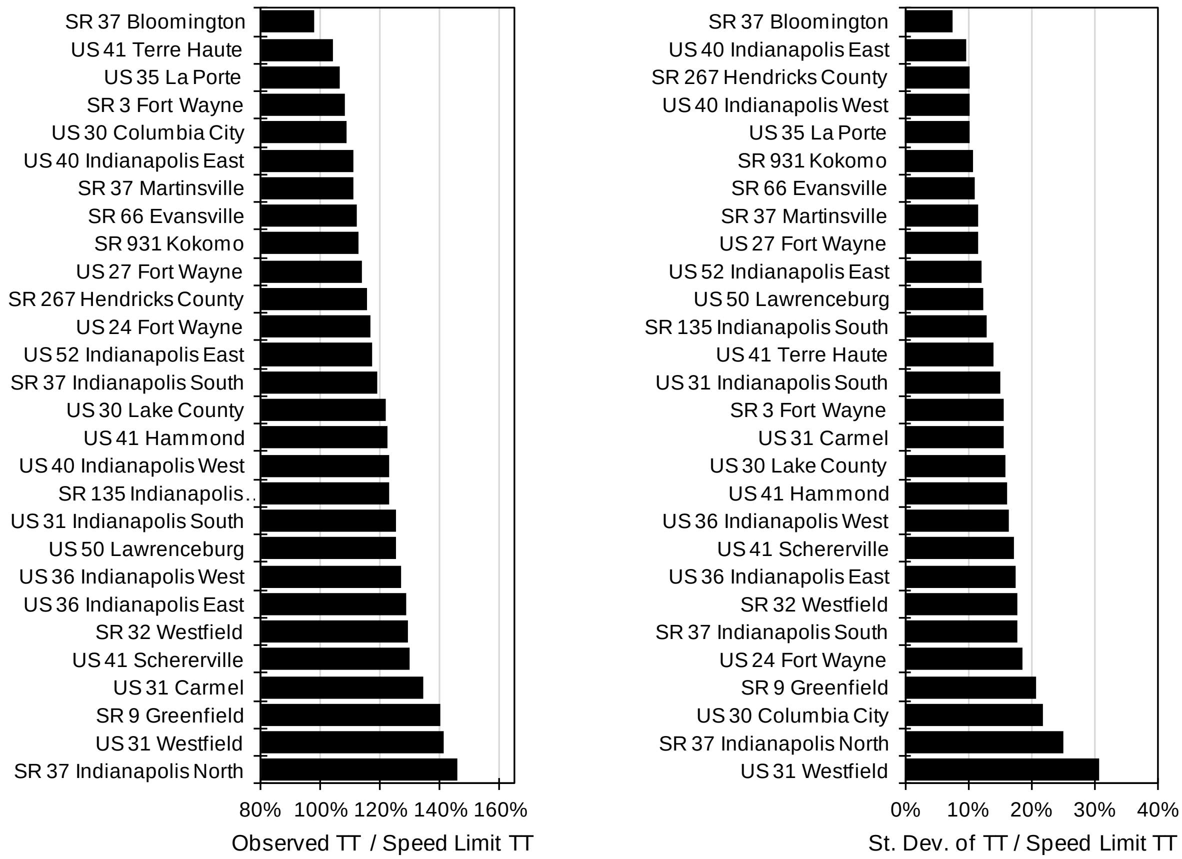
- The AM peak was defined as 6:00–9:00;
- The midday was defined as 9:00–15:00;
- The PM peak was defined as 15:00–19:00.

Data for these cohorts were populated by taking the averages and standard deviations of all the 15-minute intervals occurring on Wednesdays from January–July 2014, as described previously. This yielded a normalized average (x'_T) and a normalized standard deviation (s'_T) for each direction on each arterial for each TOD cohort.

When identifying an arterial route as a candidate for corrective action (such as traffic signal retiming), it is more useful to have a singular index for both directions of the roadway than to have two separate directions, because the action will affect both directions. To come up with a singular value for each arterial route, the *maximum* value of the two directions was selected. The rationale behind this choice is that during most times of day there tends to be a dominant direction, and an average of two directions would hide instances of poor performance.

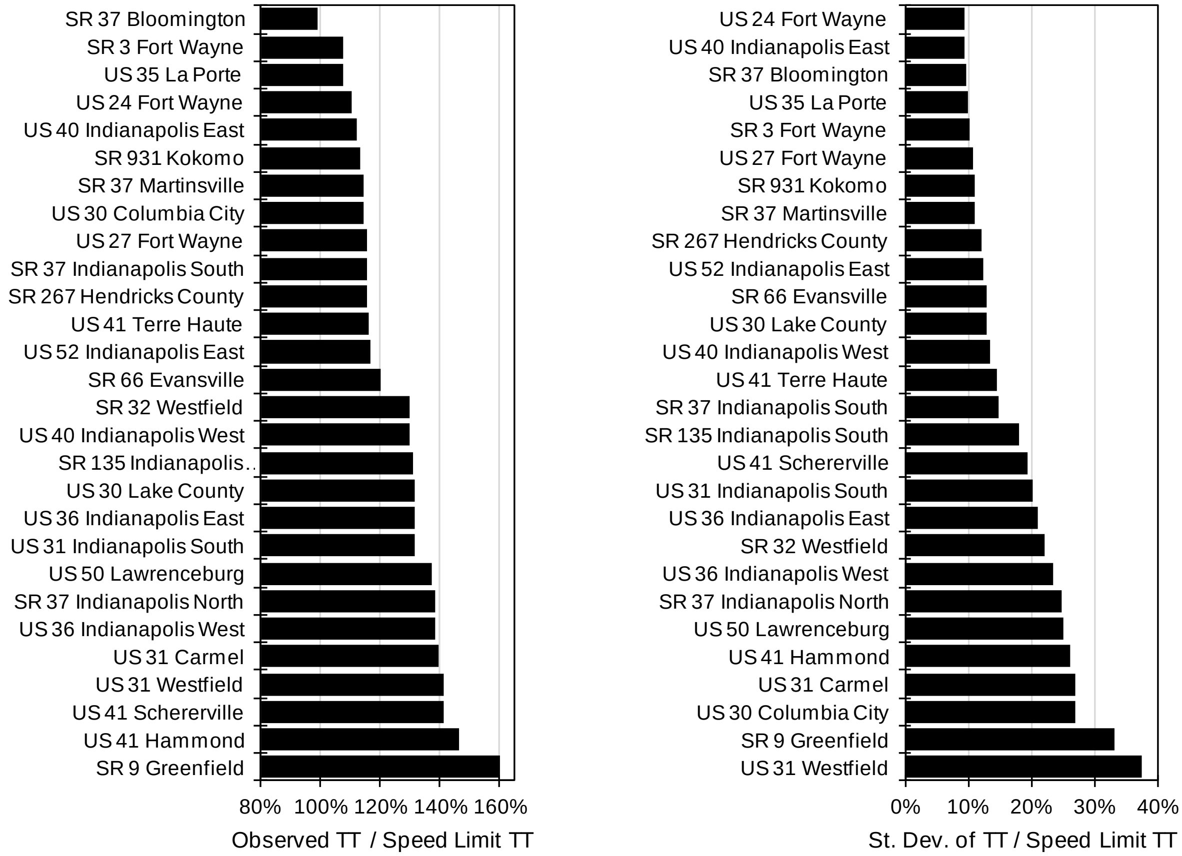
Figure 7 shows rank-ordered lists of the arterial routes according to the normalized average travel time (Figure 7a) and the normalized standard deviation of travel time (Figure 7b), for the AM peak. Figure 8 repeats this representation, for the PM peak. This data view allows overall trends to be visualized.

- All of the arterial routes, with one exception, have normalized travel times greater than 100%. This is as expected, given that delay is induced by traffic control on these routes. One particular roadway, SR 37 in Bloomington, has a value that is consistently lower than 100%. Notably, this route has the fewest number of traffic signals per mile of all the arterials in this study, having characteristics similar to a limited-access route along part of its length.
- The distribution reveals that a relatively small portion of the entire group experiences pronounced excessive travel times or unreliability. The same routes tend to appear in the same spots in the distribution. For example, SR 9 in Greenfield tends to have consistently high normalized average and standard deviations of travel time, and appears near the bottom of the list.



(a) Sorted by normalized average travel time. (b) Sorted by normalized standard deviation of travel time.

Figure 7. Arterial ranking: AM Peak (6:00–9:00).
Data shown for all Wednesdays, January–July 2014.



(a) Sorted by normalized average travel time.

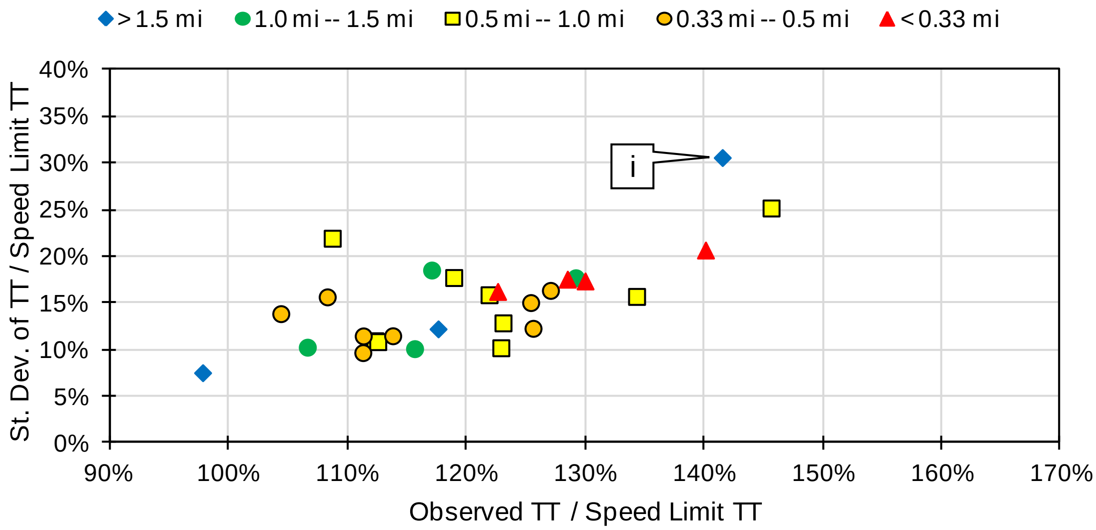
(b) Sorted by normalized standard deviation of travel time.

Figure 8. Arterial ranking: PM Peak (15:00–19:00).
Data shown for all Wednesdays, January–July 2014.

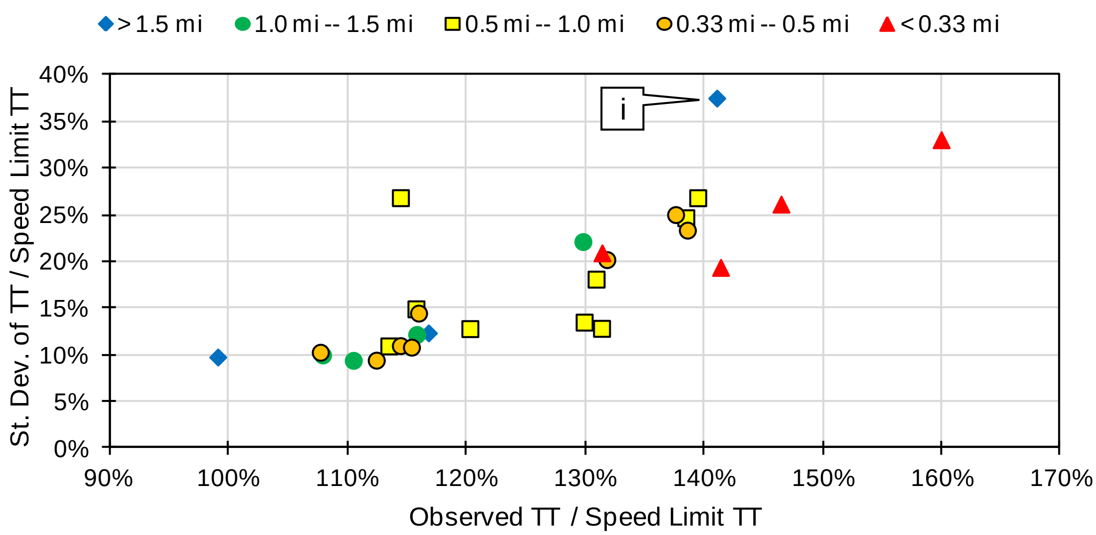
Figure 9 combines the two metrics by plotting the unreliability measure (s'_T) against the measure of central tendency (x'_T). Figure 9a shows this plot for the AM peak cohort while Figure 9b shows the PM peak. Each data point represents the value for one arterial route. The points are divided into five groups according to the density of traffic signals occurring on the route. In terms of performance, it is more desirable for the points to be near the bottom left side of the plot, which indicates an average travel time closer to the speed limit, with less variability. The further upward and to the right that the points lie, the poorer the performance.

The plots reveal a tendency (although the trend is not extremely pronounced) for those arterial routes with a higher density of traffic signals to have higher travel times and greater variability than those with fewer traffic signals. For example, in Figure 9b, the four routes with a spacing of less than one-third of a mile are situated further to the right than most of the others—but not all. The trend is less apparent in the AM peak (Figure 9a). This follows expectations, since traffic signals tend to induce delay and variability. However, the trend is perhaps less straightforward than what may have been anticipated. There difference is rather small between systems with an average spacing of greater than a mile and those with less than half a mile, for example.

One interesting outlier appearing in both plots is indicated by callout “i”. This is US 31 in Westfield, IN, which features only two intersections along the defined route. In fact, this route had the lowest signal density of all the arterials in the study. However, during much of the study period, this roadway was the site of an active work zone, which appears to have greatly increased both the travel time and the unreliability of the travel time.



(a) AM Peak (6:00–9:00)



(b) PM Peak (15:00–19:00)

Figure 9. Unreliability versus central tendency.
Legend shows average distance between traffic signals.
Data shown for all Wednesdays, January–July 2014.

Composite Index for Prioritizing Arterials

The final step in producing a singular ranking index was to combine the normalized average travel time and normalized standard deviation of travel time, and then find the average across all times of day. Based on the idea that points in the upper right hand regions of Figure 9a and Figure 9b have less desirable performance, an index that measures the distance into that region was developed:

$$\text{Index}_{\text{T}} = 100 \cdot \sqrt{\left(\max\{0, x'_T - 1\}^2 + \left(w \cdot s'_T\right)^2\right)} \qquad \text{Equation 7}$$

Here, the index is provided for time series *T* based on the normalized average of travel times x'_T and the normalized standard deviation s'_T. The variable *w* is a weighting factor that allows analyst to attribute greater or lesser value to the impact of unreliability. For this study, a value of $w = 1$ was used. This function only considers normalized average travel times greater than 100% as contributing any value to the index. Routes with a travel time of less than 100% would simply have a value of zero for the first term.

Table 1 shows the overall results for all of the arterial routes considered in the study, sorted from highest to lowest values of the composite index, which is found by taking the average of the individual indices of the AM peak, midday, and PM peaks. The individual values are also shown for each arterial. This ranking makes it possible to prioritize routes according to their travel characteristics, with those at the top of the list having the most need for improvement.

Many routes appearing high in this list are major commuter arterials, such as SR 37 on the north side of Indianapolis, or US 31 in Carmel. However, the worst-performing arterial, SR 9 in Greenfield, is not only a commuter thoroughfare but also the principal street in the city of Greenfield, providing the only real route from Interstate 70 to the center of town. While its operational characteristics are likely well-known to those who travel it daily, this is less likely to be known at the agency-wide level. Even if it were, there is no immediate reason to suspect that this particular roadway would have worse performance than what would seem to be busier routes in denser urban areas. This demonstrates the potential value in using speed data to assist operational staff to make better informed decisions. It is not difficult to envision the expansion of this list to include the remaining non-Interstate routes in Figure 1, to identify additional opportunities for system improvement.

Table 1. Final ranking of arterial routes. Data for all Wednesdays, January–July 2014.

Arterial Section	AM		Midday		PM		AM Index	Midday Index	PM Index	Composite Index
	x'_T	s'_T	x'_T	s'_T	x'_T	s'_T				
SR 9 Greenfield	1.25	0.17	1.42	0.26	1.39	0.24	29.8	49.1	45.9	41.6
SR 37 Indianapolis North	1.35	0.19	1.33	0.17	1.35	0.21	39.7	37.3	41.4	39.4
US 31 Carmel	1.33	0.14	1.33	0.17	1.37	0.23	35.7	36.9	43.6	38.7
US 41 Schererville	1.28	0.15	1.33	0.15	1.39	0.18	38.7	35.4	41.9	38.6
US 31 Westfield	1.31	0.23	1.29	0.21	1.32	0.27	31.9	35.9	43.4	37.1
US 36 Indianapolis West	1.24	0.14	1.32	0.15	1.37	0.21	28.4	35.1	42.4	35.3
US 41 Hammond	1.18	0.15	1.32	0.17	1.38	0.20	23.3	36.3	42.9	34.2
US 36 Indianapolis East	1.27	0.16	1.30	0.15	1.30	0.18	31.0	33.9	35.1	33.3
US 50 Lawrenceburg	1.24	0.12	1.29	0.12	1.32	0.19	26.9	31.8	37.5	32.1
US 31 Indianapolis South	1.23	0.13	1.30	0.14	1.31	0.17	26.7	33.3	35.1	31.7
US 30 Lake County	1.20	0.13	1.27	0.13	1.29	0.12	23.8	29.9	31.3	28.3
SR 135 Indianapolis South	1.22	0.12	1.26	0.11	1.27	0.16	24.6	27.8	31.5	28.0
US 40 Indianapolis West	1.21	0.09	1.24	0.09	1.26	0.12	22.6	25.8	28.7	25.7
SR 66 Evansville	1.12	0.10	1.17	0.10	1.19	0.11	17.5	27.2	25.6	23.4
SR 267 Hendricks County	1.13	0.09	1.16	0.09	1.15	0.11	15.2	20.3	21.7	19.1
US 52 Indianapolis East	1.15	0.11	1.13	0.10	1.13	0.10	18.6	18.1	19.3	18.7
SR 931 Kokomo	1.12	0.10	1.16	0.10	1.13	0.11	15.7	18.2	18.4	17.4
US 27 Fort Wayne	1.13	0.11	1.14	0.09	1.13	0.09	18.9	16.5	16.6	17.3
SR 32 Westfield	1.13	0.14	1.13	0.13	1.13	0.14	15.5	19.0	16.5	17.0
US 24 Fort Wayne	1.15	0.16	1.12	0.11	1.09	0.09	11.9	21.0	18.0	17.0
US 40 Indianapolis East	1.10	0.09	1.14	0.09	1.12	0.09	21.7	15.9	12.8	16.8
SR 37 Indianapolis South	1.12	0.13	1.09	0.09	1.14	0.13	17.8	12.6	18.6	16.3
SR 37 Martinsville	1.09	0.11	1.12	0.13	1.11	0.10	16.4	16.6	15.9	16.3
US 30 Columbia City	1.05	0.17	1.11	0.25	1.11	0.23	14.1	17.5	14.7	15.4
US 41 Terre Haute	1.03	0.12	1.15	0.15	1.13	0.13	13.2	16.4	14.7	14.8
SR 3 Fort Wayne	1.06	0.13	1.07	0.11	1.06	0.09	14.0	12.5	11.1	12.5
US 35 La Porte	1.05	0.09	1.03	0.07	1.05	0.08	9.9	7.9	9.9	9.2
SR 37 Bloomington	0.92	0.07	0.91	0.06	0.92	0.08	6.9	6.2	8.1	7.1

CONCLUSIONS

Study Outcomes

This study examined travel times on a variety of arterial routes throughout the state of Indiana as a pilot study on analyzing arterial mobility and ranking the routes by performance. A methodology was presented in which the individual minute-by-minute speeds were aggregated into 15-minute bins and converted into travel times, which were combined into time series cohorts for analysis purposes. Measures of central tendency and variability (unreliability) were normalized to account for the variation in route distances and speeds. The speed limit travel time was used for normalization.

Three time-of-day cohorts were defined, reflecting the AM peak, midday, and PM peak. Data was compiled for all of the Wednesdays occurring from January through July 2014. Plotting the unreliability against the average value showed an interesting trend with respect to the density of traffic signals on the arterial routes. Those routes with a greater density of traffic signals tended to have higher average travel times and less reliability. Finally, a ranking of arterials by performance criteria was established, incorporating both the average value of the travel time as well as its unreliability into a composite index.

Future work will focus on improving the methodology by migrating toward data sources with more uniform segment definitions, and expanding the analysis to include a greater number of arterial routes. In particular, the incorporation of traffic volumes will provide additional information that will enable corridors to be ranked according by usage in addition to travel time characteristics. Finally, future research will examine whether metrics other than the average and standard deviation can better represent the central tendency and degree of variation in the measured speeds, and whether the 15-minute binning methodology could be improved, for example by using a rolling horizon.

Implementation

In recent years, practitioners are increasingly asked to demonstrate accountability by measuring and reporting system performance. The methodology presented here was repeated to cover a longer time period, and the results were included in the 2013-2014 Indiana Mobility Report (*2*). Practitioners who would use a similar ranking methodology would need to select an appropriate data collection methodology appropriate to their resource levels and the geographic distribution of their assets. Although crowd-sourced probe vehicle speed data was used in this case, the methodology could use any form of estimated or measured travel times on the arterial sections.

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